

Higgs Pair Production at the LHC in Models with Universal Extra Dimensions

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Abstract

In this letter we study the process of gluon fusion into a pair of Higgs bosons in a model with one universal extra dimension. We find that the contributions from the extra top quark Kaluza-Klein excitations lead to a Higgs pair production cross section at the LHC that can be significantly altered compared to the Standard Model value for small values of the compactification scale.

1 Introduction

In spite of the great experimental successes of the Standard Model (SM), we still do not have a direct test of its symmetry breaking sector. In fact, one may say that there is a tension arising from the indirect bounds on the Higgs mass coming from the loop structure and precision measurements, which favours a Higgs mass that is already excluded by direct searches. In addition, we already know that the SM is incomplete, since it does not provide for a viable dark matter candidate and for neutrino masses and mixings.

On a more theoretical side, the SM is not satisfactory due to the triviality and hierarchy problems in the Higgs sector. These problems suggest that the Higgs sector should be viewed as an effective theory valid up to a certain energy scale. The traditional solutions to these problems used to be represented by two broad classes of models: supersymmetry and technicolor.

Recently a third class of solutions has been proposed, involving the existence of extra space-like compact dimensions [1]. This class can be further divided in three different classes depending on the fields that can propagate in the extra dimensions and the geometry of these extra dimensions. In this letter we will concentrate on the so-called models of Universal Extra Dimensions (UED), where all fields can propagate in the flat compact extra dimensions [2]. An

important property of UED arises from momentum conservation in the extra dimensions. This implies that KK number is conserved in all tree level vertices. As a consequence contributions to electroweak observables arise only from loops of KK particles allowing compactification scales as low as 500 GeV [3].

We are interested in the consequences of this model for Higgs boson production at hadron colliders. The analysis of single Higgs production in gluon fusion process was done by Petriello [4] and a significant enhancement compared to the SM was found.

Higgs pair production via gluon fusion in the SM was studied in [5] and is an interesting process since it could give information on the Higgs boson cubic coupling. Hence it is important to examine possible deviations from SM predictions in different models. For instance, Higgs pair production in Little Higgs models was studied in [6].

In this paper we study the modifications of the Higgs pair production cross section via gluon fusion in UED.

2 Model and relevant masses and couplings

In models of UED all fields are allowed to propagate in the bulk and hence they all have an associated Kaluza-Klein (KK) tower. We will work in the case of one additional compact dimension. In order to retain the zero modes corresponding to SM particles it is usual to compactify the extra dimension in an orbifold S_1/Z_2 , defined by the identification $y \rightarrow y + \pi R$, where y is the 5th dimension coordinate and R is the compactification radius, and demand that the fields with zero modes to be even under the transformation $y \rightarrow -y$.

After compactification the relevant fields for our purposes (Higgs doublet H , top quark singlet t , top quark doublet Q and gluon field G) will have the usual KK expansion:

$$H(x^\mu, y) = H^0(x)\chi^{(0)} + \sum_{n=1}^{\infty} [H^{(n)}(x)\chi^{(n)}(y)] \quad (1)$$

$$t(x^\mu, y) = t_R^0(x)\chi^{(0)} + \sum_{n=1}^{\infty} [t_R^{(n)}(x)\chi^{(n)}(y) + t_L^{(n)}(x)\phi^{(n)}(y)] \quad (2)$$

$$G_\mu^a(x^\nu, y) = G_\mu^{a(0)}(x)\chi^{(0)} + \sum_{n=1}^{\infty} [G_\mu^{a(n)}(x)\chi^{(n)}(y)] \quad (3)$$

$$Q(x^\mu, y) = Q_L^0(x)\chi^{(0)} + \sum_{n=1}^{\infty} [Q_L^{(n)}(x)\chi^{(n)}(y) + Q_R^{(n)}(x)\phi^{(n)}(y)] \quad (4)$$

$$G_5^a(x^\nu, y) = \sum_{n=1}^{\infty} [G_5^{a(n)}(x)\phi^{(n)}(y)] \quad (5)$$

where $\chi^{(n)}(y)$ and $\phi^{(n)}(y)$ are orthogonal basis:

$$\chi^{(n)}(y) = \frac{1}{\sqrt{\pi R}} \cos \frac{ny}{R}, \quad \chi^{(0)} = \frac{1}{\sqrt{2\pi R}}, \quad \phi^{(n)}(y) = \frac{1}{\sqrt{\pi R}} \sin \frac{ny}{R}. \quad (6)$$

The couplings of KK top quarks with gluons and Higgs field that enter in our computation are derived from the lagrangian:

$$\mathcal{L}_{top} = \int_{-\pi R}^{\pi R} dy \int d^4x \{ i\bar{Q} \not{D} Q + i\bar{t} \not{D} t + [\lambda_5^t \bar{Q} i\sigma_2 H^* t + h.c.] \}, \quad (7)$$

where the covariant derivative is:

$$\not{D} = \Gamma^M (\partial_M - ig_5 T^a G_M^a), \quad (8)$$

M is a Lorentz index with values $M = 0, 1, 2, 3$ and 5 (we will use lower case greek index like $\mu = 0, 1, 2, 3$ to denote the usual non-compact dimensions), $\Gamma^M = (\gamma^\mu, i\gamma^5)$ are the 5-d Dirac matrices, g_5 and λ_5^t are the 5-d QCD and Yukawa coupling constants respectively and T^a is the usual color group generator.

Considering only the coupling to the Higgs zero mode, which after spontaneous symmetry breaking is written in terms of its vacuum expectation value $v = 246$ GeV as

$$H^{(0)} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h^{(0)}(x) \end{pmatrix} \quad (9)$$

and using the relation between the 5-d and 4-d top Yukawa coupling, $\lambda^t = \frac{\lambda_5^t}{\sqrt{2\pi R}}$, with the zero mode top quark mass given as usual by $m_t = \frac{\lambda^t v}{\sqrt{2}}$, one finds that the mass eigenstates of the KK top quark tower are

$$T_R^{(n)} = \begin{pmatrix} t_{1R}^{(n)} \\ t_{2R}^{(n)} \end{pmatrix} \quad T_L^{(n)} = \begin{pmatrix} t_{1L}^{(n)} \\ t_{2L}^{(n)} \end{pmatrix}. \quad (10)$$

These mass eigenstates are related to the original states by

$$T_R^{(n)} = U_R^{(n)} \begin{pmatrix} \tilde{t}_R^{(n)} \\ t_R^{(n)} \end{pmatrix} \quad T_L^{(n)} = U_L^{(n)} \begin{pmatrix} \tilde{t}_L^{(n)} \\ t_L^{(n)} \end{pmatrix} \quad (11)$$

where $\tilde{t}_L^{(n)}$ and $\tilde{t}_R^{(n)}$ denote the upper components of the doublets $Q_L^{(n)}$ and $Q_R^{(n)}$ respectively. The orthogonal matrices $U_R^{(n)}$ and $U_L^{(n)}$ are given by

$$U_R^{(n)} = \begin{pmatrix} \cos \frac{\alpha^{(n)}}{2} & \sin \frac{\alpha^{(n)}}{2} \\ -\sin \frac{\alpha^{(n)}}{2} & \cos \frac{\alpha^{(n)}}{2} \end{pmatrix} \quad U_L^{(n)} = \begin{pmatrix} \cos \frac{\alpha^{(n)}}{2} & \sin \frac{\alpha^{(n)}}{2} \\ \sin \frac{\alpha^{(n)}}{2} & -\cos \frac{\alpha^{(n)}}{2} \end{pmatrix} \quad (12)$$

where $\sin \alpha^{(n)} \equiv \frac{m_t}{m_{t,n}}$ and $\cos \alpha^{(n)} \equiv \frac{m_n}{m_{t,n}}$, with $m_{t,n}^2 \equiv m_t^2 + m_n^2$ and $m_n = \frac{n}{R}$. The two top KK towers mass eigenstates, $t_1^{(n)}$ and $t_2^{(n)}$, have a degenerate mass given by $m_{t,n}$.

The couplings of the top KK tower states with gluons are simply given by

$$g_s \sum_{n=1}^{\infty} \left[\bar{t}_1^{(n)} g^{(0)} t_1^{(n)} + \bar{t}_2^{(n)} g^{(0)} t_2^{(n)} \right] \quad (13)$$

whereas the coupling to the zero mode Higgs boson can mix $t_1^{(n)}$ and $t_2^{(n)}$:

$$\frac{m_t}{v} h^{(0)} \sum_{n=1}^{\infty} \left[\sin \alpha^{(n)} \left(\bar{t}_{1L}^{(n)} t_{1R}^{(n)} + \bar{t}_{2L}^{(n)} t_{2R}^{(n)} \right) + \cos \alpha^{(n)} \left(\bar{t}_{1L}^{(n)} t_{2R}^{(n)} - \bar{t}_{2L}^{(n)} t_{1R}^{(n)} \right) + h.c. \right] \quad (14)$$

Notice that the top KK Yukawa couplings are proportional to the top quark mass and hence their effects decouple for higher KK modes.

3 Model implementation and results

We implemented the new particles and couplings in FeynArts [7] for an arbitrary number of KK modes. We then use FormCalc [8] to perform the computation of traces and the reduction of the tensor one-loop integrals to scalar Passarino-Veltman integrals [9]. Finally, LoopTools [10] computes numerically the integrals and CUBA [11] integrates over phase space to find the cross section. We verified that in the case of single Higgs production in UED, where only a triangle diagram contributes, the program reproduces both analytically and numerically the results obtained by Petriello [4]. We have also checked our code with the SM Higgs pair production [5].

In Figure 1 we show the diagrams that are computed for one top quark KK level. Notice the presence of 2 top KK excitations for each level and their mixture through the Yukawa coupling.

In this work we will consider compactification scales $1/R$ as low as 500 GeV, as allowed by electroweak precision measurements [3] (see also [12] for bounds coming from $b \rightarrow s\gamma$ processes) and first compute the deviations from the SM for a fixed partonic center-of-mass energy $\sqrt{\hat{s}}$ as a function of the Higgs boson mass M_H for different values of the compactification scale. We will include in the calculation a number n of KK levels such that $m_n < 10$ TeV for a given compactification scale, where one expects that the 4-dimensional effective theory starts to lose its validity [2]. For instance, we considered the contribution of 20 KK levels for $1/R = 500$ GeV. In practice, the convergence for large values of n is very rapid.

In Figure 2 we show the differences between the SM and UED contributions for the triangle and box diagrams separately. We fix $\sqrt{\hat{s}} = 1.0$ TeV and $1/R = 500$ GeV for illustration.

The triangle contribution can be understood analytically; it is given by the difference in the triangle amplitude:

$$\frac{\sigma_{UED}^{\triangle}(gg \rightarrow HH) - \sigma_{SM}^{\triangle}(gg \rightarrow HH)}{\sigma_{SM}^{\triangle}(gg \rightarrow HH)} = \frac{|A_{SM} + A_{KK}|^2 - |A_{SM}|^2}{|A_{SM}|^2}, \quad (15)$$

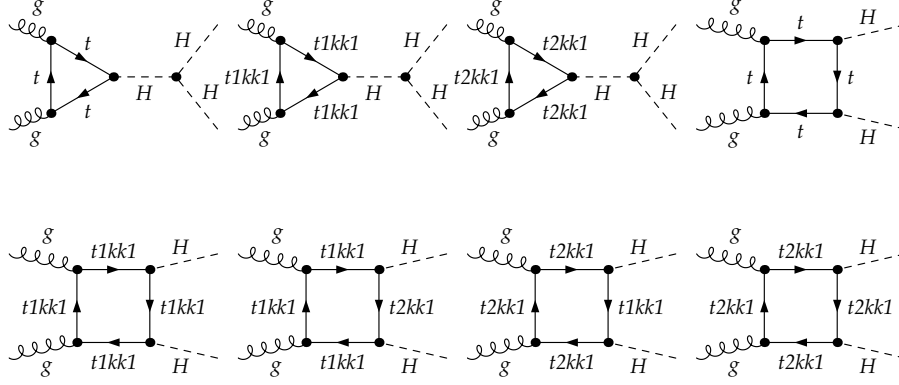


Figure 1: Feynman diagrams for the process $gg \rightarrow HH$ with the contribution from the first top quark KK modes, denoted by $t1kk1$ and $t2kk1$ in the figure. Permutations of the external lines are not shown.

where

$$A_{SM} = m_t^2 [(\hat{s} - 4m_t^2)C_0(\hat{s}, m_t^2) - 2], \quad (16)$$

$$A_{KK} = 2m_t \sum_n m_{t,n} \sin \alpha^{(n)} [(\hat{s} - 4m_{t,n}^2)C_0(\hat{s}, m_{t,n}^2) - 2], \quad (17)$$

and, as usual

$$\begin{aligned} C_0(\hat{s}, m^2) &= -\frac{2}{\hat{s}} [\arcsin(1/\sqrt{\tau})]^2 & \text{for } \tau \geq 1 \\ &= \frac{1}{2\hat{s}} \left[\log \left(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} \right) - i\pi \right]^2 & \text{for } \tau < 1 \end{aligned} \quad (18)$$

with $\tau = 4m^2/\hat{s}$. Notice that the triangle contribution is independent of the Higgs boson mass. The factor of 2 in eq. (17) is due to the presence of 2 top KK excitations for each level. Figure 3 shows the analytical result for difference in the triangle contribution only, showing the rapid convergence of the result and its agreement with the numerical computation shown in Figure 2.

The box contribution is more difficult to analyze due to the fact that many Passarino-Veltman integrals with different arguments appear in the result. This is the reason of the more complicated behavior of the box contribution depicted in Figure 2. We notice that there is a strong interference between the triangle and box contributions. The final result shows large deviations both enhancing and suppressing the cross section, depending on the Higgs boson mass. In the case of a Higgs boson lighter than $M_H = 200$ GeV, the partonic gluon fusion

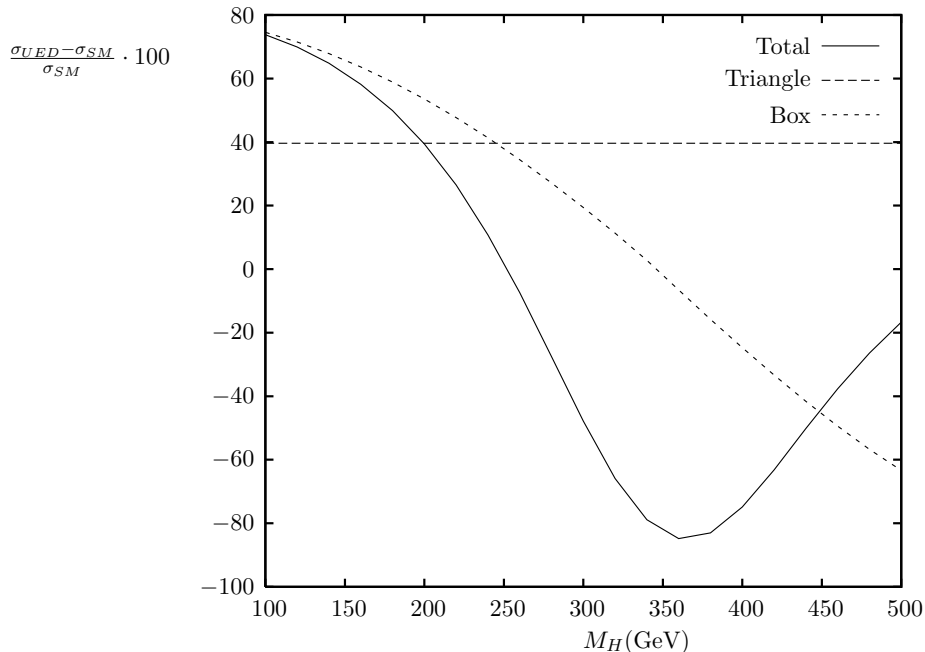


Figure 2: Deviations from SM arising separately from triangle and box contributions, together with the total deviation, as a function of the Higgs boson mass. Center-of-mass energy is fixed at $\sqrt{s} = 1$ TeV and compactification scale $1/R = 500$ GeV.

cross section can be enhanced by more than 40%. These deviations increase with partonic center-of-mass energy.

We present in Figure 4 the deviations from the SM result for the partonic gluon fusion Higgs pair production for different values of the compactification scale for a fixed value of the center-of-mass energy at $\sqrt{s} = 1$ TeV. As expected, for larger values of $1/R$ the KK modes get heavier and the deviations from the SM rapidly decreases.

The total Higgs pair production cross section at the LHC is computed in the standard way by convoluting the partonic cross section with the gluon distribution function. We used the Mathematica package implementation of the parton distribution functions of [13] with factorization and renormalization scales given by $Q^2 = \hat{s}$, $\alpha_s(M_Z) = 0.118$ and $m_t = 175$ GeV. In Figures 5 and 6 we compare the SM result as a function of the Higgs mass with the UED results with compactification scales of $1/R = 500, 700$ and 1000 GeV. Differences as large as $\pm 40\%$ can arise in these models.

Electroweak precision data puts bounds on the compactification scale as a function of the Higgs mass and these constraints decrease with increasing Higgs mass [3]. These constraints are sensitive to the top mass allowing $\frac{1}{R} = 600$ GeV

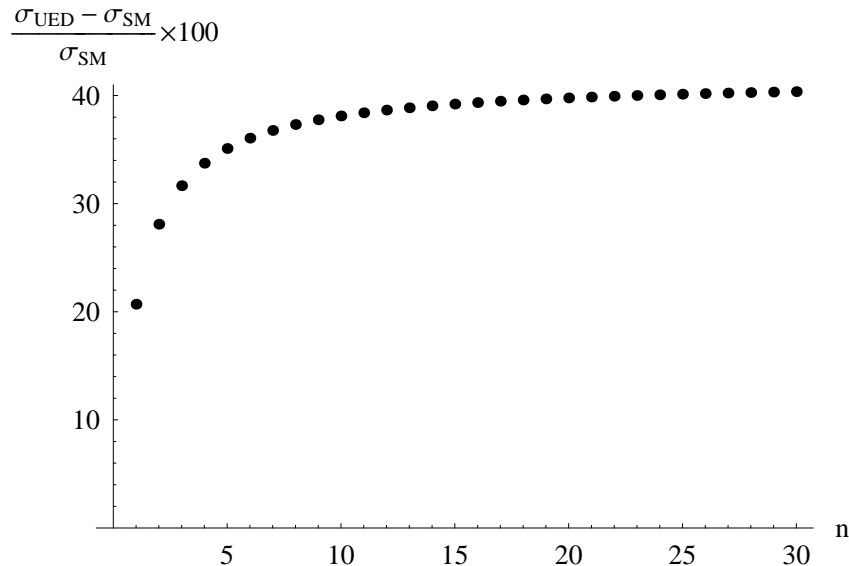


Figure 3: Analytical calculation of deviations from SM arising only from the triangle as a function of the KK level. Center-of-mass energy is fixed at $\sqrt{\hat{s}} = 1$ TeV and compactification scale $1/R = 500$ GeV.

for $m_H = 115$ GeV and $m_t = 173$ GeV, which increases in 23% the SM cross section. Bounds coming from $b \rightarrow s\gamma$ process [12] implies a compactification scale as low as 600 GeV independent of the Higgs mass. The cross section is increased by 16% for a light Higgs with mass 120 GeV and $\frac{1}{R} = 700$ GeV.

4 Conclusions

In this paper we studied the effects of UED in the gluon fusion Higgs pair production cross section. We implemented the contributions of the top KK excitations for the triangle and box diagrams and showed that the partonic cross section shows large deviations both enhancing and suppressing the cross section, depending on the Higgs boson mass. The total gluon fusion Higgs pair production cross section at the LHC can be modified by up to 23% when bounds from precision measurements are taken into account. These effects are rapidly reduced for larger values of the compactification scale.

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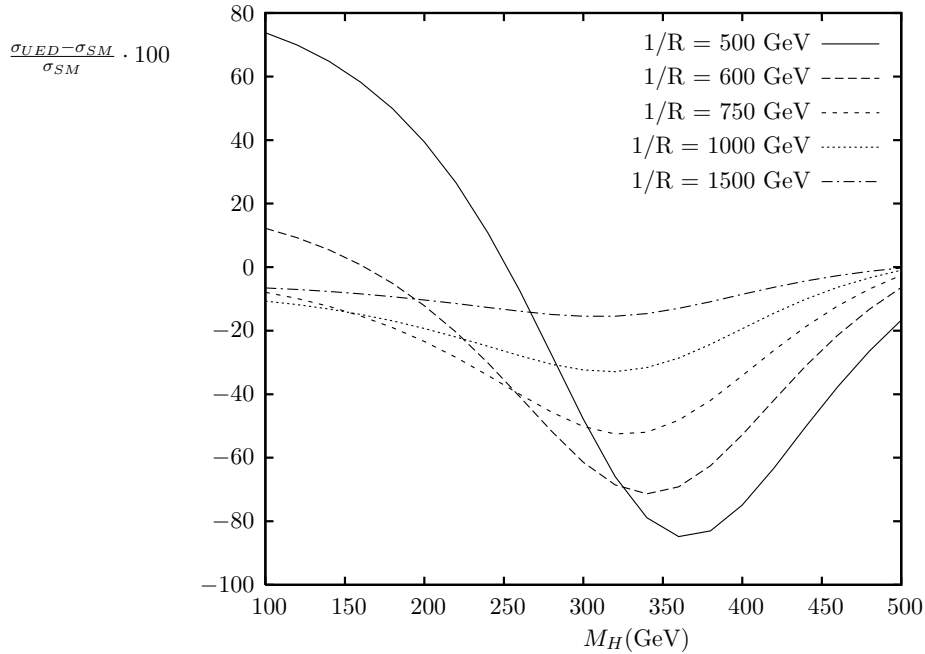


Figure 4: Deviations from SM gluon fusion Higgs pair production arising from top KK modes as a function of the Higgs boson mass for different compactification scales. Center-of-mass energy is fixed at $\sqrt{s} = 1$ TeV.

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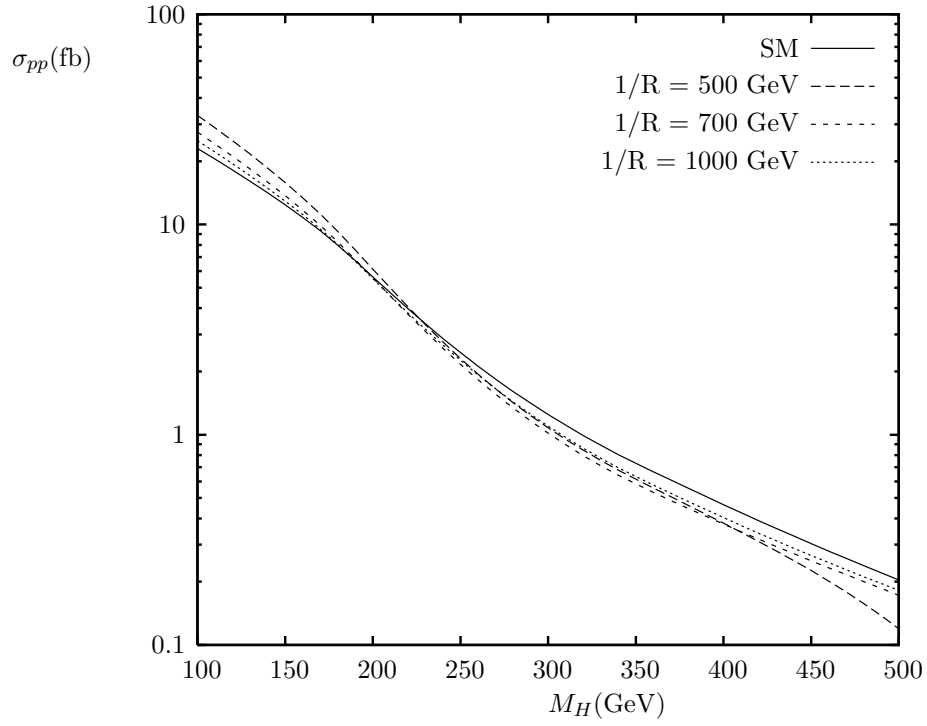


Figure 5: SM Higgs pair production cross section via gluon fusion at the LHC as a function of the Higgs mass compared with the UED result for compactification scales of $1/R = 500, 700$ and 1000 GeV.

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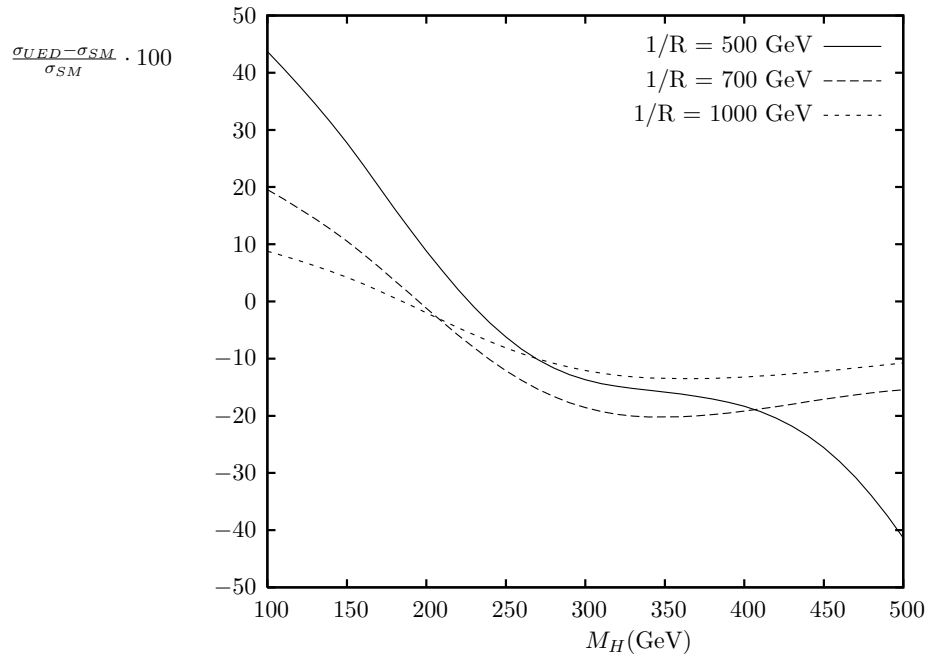


Figure 6: Deviations from SM of Higgs pair production cross section via gluon fusion at the LHC as a function of the Higgs mass for values of the compactification scales of $1/R = 500, 700$ and 1000 GeV.